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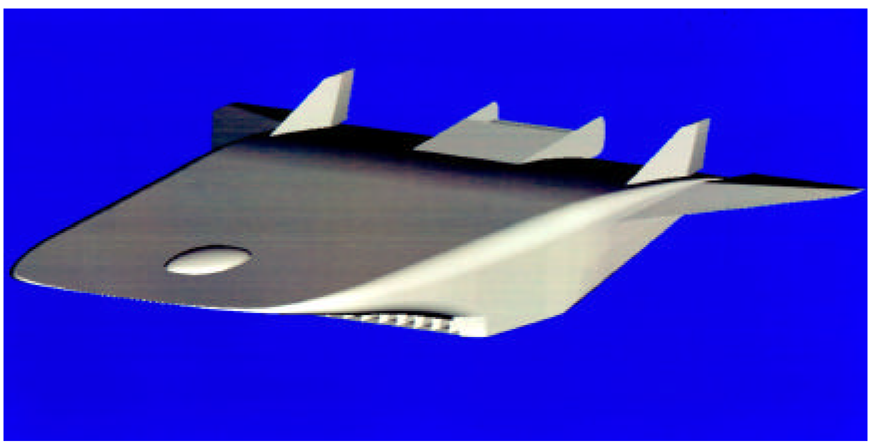

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ABSTRACT

This paper presents a Mach 23 staged two stage-to-orbit launch vehicle candidate. Previously, two stage-to-orbit launch vehicles considered subsonic, supersonic and hypersonic staging options. Studies have shown that performance optimized two stage launch vehicles have first stage performance capabilities that vary widely depending on the propulsion and type of fuel used in the first and second stage. A Mach 23 performance capable first stage could fly around the world and return from the take-off site using a boost-glide-skip trajectory profile. A Mach 23 staged first stage would be significantly less difficult to develop compared to a single stage-to-orbit launch vehicle. The usable propellant fraction for the Mach 23 rocket-based combined cycle engine powered first stage presented in this paper is 0.614 and the payload fraction is 0.033.

Previous work by the authors has shown that a Mach 23 staged vehicle is close to the performance optimum when a GEO transfer operational orbit of the payload is considered as the performance requirement for a two-stage-to- orbit vehicle. A Mach 23 first stage capable launch vehicle can operate from a single launch site without the need for down-range recovery sites and a means of returning to the launch site. During each flight the first stage returns directly to the take-off site on an unpowered boost-glide-skip trajectory.

INTRODUCTION

Based on the National AeroSpace Plane (NASP) experience and the current status of with the X-33, it is generally concluded that a single stage-to-orbit launch vehicle is very difficult to achieve at this time, independent of whether the vehicle is rocket, or air-breathing powered. While an SSTO design would be desirable from a cost and operational perspective, the technical risk remains very high. As a result, advanced reusable launch vehicle design attention has turned to two-stage-to-orbit (TSTO) concepts.

During the 1970s and 1980s a number of two-stage launch vehicles were proposed, both in the United States and in foreign countries. Recently, Dr. Fred Billig led an Air Force Scientific Advisory Board study that completed a comprehensive parametric study of single- and two-stage launch vehicles considering a wide selection of propellants and propulsion systems in each stage. On the bases of past studies, it is generally concluded that the performance optimization of a TSTO launch vehicle is obtained by staging between Mach 5-10, depending on the propellants and propulsion system used in both the first and second stages. These studies also indicated that the minimum cost two-stage reusable launch vehicle would have subsonic or low supersonic staging. There is not complete consensus on whether an SSTO, or a TSTO, launch vehicle would provide the lowest cost per pound to orbit, though, it is generally felt that a SSTO would be less costly to develop and operate than a TSTO reusable launch vehicle.

This paper presents for consideration a Mach 23 staged TSTO reusable launch vehicle candidate. A Mach 23 first stage was selected based on previous work by the authors on a rocket-based combined cycle engine powered hypersonic global range aerospace plane that used a boost-glide-skip trajectory profile to achieve an unrefueled global range capability. An assessment of the boost-glide-skip trajectory flight profile is contained in Reference 1. During the skip-glide portion of the trajectory the vehicle is unpowered. It was found that a cut-off speed of approximately Mach 23 was needed to achieve a global range capability using this type of trajectory profile. Further study of upper stages for a TSTO launch vehicle indicated that a staging Mach number of 23 did not impose a severe performance penalty when compared to a Mach 5-10 staged TSTO reusable launch vehicle (references 2 and 3).

Prior to the International Space Station, the reference performance mission for a SSTO launch vehicle was usually a due East, 100 n. mi. mission from Kennedy. A Polar mission excursion was usually included in the analysis. A polar mission can reduce the payload by approximately 50% compared to a due East launch. Current studies have used a mission to the International Space Station as the reference mission. Shifting the performance reference mission to the International Space Station makes it even more difficult to achieve closure on a SSTO design concept. As the mission velocity capability of a reusable TSTO launch vehicle increases the optimum staging Mach number increases.

An air-breathing Mach 23 first stage has a significantly lower usable propellant fraction requirement compared to a SSTO capable first stage (reference 4). An SSTO performance capable first stage has a usable propellant fraction of 0.790 compared to a Mach 23 performance capable first stage usable propellant fraction of 0.614.

The second stage for a SSTO capable first stage and a Mach 23 capable first stage would have about the same dry weight. The difference in second stage dry weight would be due to the larger propellant tanks needed in the second stage for the Mach 23 design to accommodate the propellants needed to provide the additional 2,500 fps to achieve orbital velocity. The cost of the two upper stages would, therefore, be about the same in each case as the difference in dry weight is only that needed to increase propellant tank volume. The first stage of a Mach 23 staged design should cost less than a SSTO performance capable first stage due to the reduction in useable propellant fraction for the Mach 23 design. Overall, a Mach 23 staged TSTO launch vehicle could cost less than a TSTO vehicle with an SSTO performance capable first stage.

Figure 1 presents the characteristics of a typical boost-glide-skip flight profile. The idea of achieving a global-range performance capability using a boost-glide-skip flight profile is not new. Dr. Eugene Sanger and Dr. Irene Bret first proposed a boost-glide-skip global-range flight profile for a German rocket-powered bomber in August of 1944. Since the publication of Reference 1, additional work has been done on boost-glide-skip global-range flight profiles by the ANSER team as part of a NSF grant to determine the impact of Russian AYAKS technologies on reusable launch vehicles. The use of a global range boost-glide-skip flight profile has several advantages compared to a ballistic flight profile. The advantages include a significant reduction in the required propellant fraction compared to an SSTO performance capability first stage. The energy to achieve a global range performance capability using a boost-glide-skip trajectory profile requires approximately 15% less velocity than that required for an SSTO performance capability.

A global range performance capable first stage has the potential for less complex flight operations. After the deployment of the upper stage and payload exoatmospherically, the first stage returns to the launch site using the global range boost-glide-skip trajectory. No additional launch sites are required to recover the first stage, as is the case for a rocket-powered TSTO vehicle using a “pop-up” trajectory profile proposed by the Air Force Research Laboratory. Down-range landing sites and a method to return the first stage to the take-off site are not needed, in the case of the Mach 23 staged TSTO design.

A further advantage of a Mach 23 staged TSTO design is associated with the global-range boost-glide-skip trajectory. Each boost -glide-skip cycle apogee provides an opportunity to deploy a payload exoatmospherically, and each atmospheric perigee provides an opportunity to use aerodynamic forces to change the trajectory profile.

DESIGN CONCEPT

To evaluate the performance of the proposed Mach 23 staged TSTO design concept, a reference combined cycle engine powered SSTO design concept was modified to function as a Mach 23 performance capable first stage (see reference 5 for the SSTO design concept used for this purpose). The first stage of the TSTO design concept is a derivative of the NASA Access to Space air-breathing SSTO design concept. The Access to Space air-breathing SSTO design concept was formulated by the NASA LaRC Hypersonic Systems Group after the termination of the NASP X-30 program. NASA LaRC people have continued to update the design to reflect the latest subsystem technology forecast and engine performance data. The baseline mission is the delivery of 25,000 lbs. of payload to the International Space Station. This equates to a payload of approximately 40,000 lbs to a 100 n. mi., 28-degree inclination orbit.

FIRST STAGE – The Access to Space vehicle rocket engine located along the trailing edge was removed and the air-breathing combined cycle propulsion system was replaced by the Aerojet combined cycle “strutjet” propulsion system in the reference vehicle. See reference 6 for details of the Aerojet rocket-based combined cycle engine. The Aerojet engine integrates a liquid hydrogen/oxygen rocket into the air-breathing combined cycle ram-scramjet engine to achieve a rocket ejector ram-scramjet combined cycle engine. The rocket engine is integrated into the walls of the ram-scramjet engine struts. The effective thrust-to-weight ratio of the installed rocket engine is several hundred compared to a conventional hydrogen-oxygen rocket engine of 70-90. Both the rocket and ram-scramjet engines share a common exhaust nozzle. The overall configuration of the first stage is similar to the Access to Space SSTO configuration. NASA Ames people modified the Access to space configuration to better accommodate the Aerojet engine. Eight individual propulsion modules were integrated into the 175 ft long airframe. Aerojet provided engineering data for the strutjet system. Aero data were provided by NASA Ames.

Figure 2 shows the reference Access to Space class SSTO design concept with the Aerojet engine, and a cutaway of the combined cycle engine module used to define the Mach 23 first stage. The performance of the first stage is shown on figures 3-6. The Mach 23 staged TSTO reusable launch vehicle takes off horizontally using the ejector rocket engine cycle. The air-breathing part of the ejector ram-scramjet engine cycles is turned off at Mach 12. The rocket engine is turned off when Mach 23 is achieved.

Figure 3 presents an altitude - time plot of the boost-glide-skip global range trajectory for the first stage. The apogee of the trajectory is approximately 425,000 ft. Variations in altitude range from approximately 250,000 ft maximum down to approximately 50,000 ft. It takes 12 complete cycles to travel approximately 21,000 n. mi. around the world in 7,200 seconds (2 hours). The maximum speed is approximately 23,500 fps at first stage burnout. The maximum angle of attack is approximately 3 degrees. During the boost phase the maximum dynamic pressure is less than 2200 psf. During the skip-glide part of the trajectory the maximum dynamic press is approximately 350 psf.

Figures 8-11 present the required ideal velocity requirements. Both the drag and gravity losses incurred during the powered part of the boost-glide-trajectory are plotted. It is interesting to note that the required ideal velocity required to achieve Mach 23 is approximately 35,000 fps. This is low for an air-breathing powered reusable launch vehicle. The Access to Space SSTO design concept requires about 40,0000 fps to achieve Mach 23. The difference in the velocity requirements is due to two factors. First, the Mach 23 staged vehicle terminates the air-breathing part of the trajectory at Mach 12 compared for Mach 16 for the Access to Space SSTO design, and secondly the take-off thrust to weight for the Mach 23 staged vehicle is approximately 1, whereas, the Access to Space SSTO design has a thrust to with ratio at take-off less then 0.5. The ANSER team found during the NASA Highly Reusable Space Transportation study that a high take-off thrust-to-weight ratio during take-off and climb dramatically reduced ideal velocity requirements. A take-off thrust-to-weight ratio of approximately 1.3 was optimum for the reference design concept (reference 5).

Table 1 provides a detailed weight breakdown for the Mach 23 performance first stage. The weight margin is 15%. The 706,572 lbs gross take-off weight (GTOW) vehicle can deliver 23,000 lbs of payload to Mach 23. Figure 14 shows the sensitivity of the payload with GTOW.

SECOND STAGE - An Air Force Research Laboratory upper-stage study looked at a wide range of parameters affecting the performance of a TSTO reusable launch vehicle using a SSTO derived first stage and a "pop-up" trajectory profile (reference 7). Second stage variables considered included propellants, propulsion (solid, pressure fed, and pump fed), and propellant tank design configuration (torroidal, isogrid, stacked isogrid, and cylinder). An important feature of the study was the constraint s placed on the first stage payload volume. Two sizes were considered in the Air Force Laboratory study, 7.62m by 3.66m and 9.14m by 4.57m. This analysis considered the large payload bay to determine the heaviest second stage and payload weight capability.

Figure 12 shows the GEO payload capability of a TSTO reusable launch vehicle as a function of first stage orbital velocity deficiency. A typical "knee" chart, as they were called in reference 7, was used to show the maximize performance conditions for of a SSTO capable first stage using a " pop-up" trajectory profile. These data indicate that for a first stage orbital velocity shortfall of approximately 2500 fps, the spacecraft mass delivered into GEO orbit is near maximum, independent of propellant combination for toroidal propellant tanks. The 2500 fps shortfall Corresponds directly with the Mach 23 capable first stage option. The first stage payload weight and volume constraints on the second stage are key factors in determining theses results. However, the volume constraints on the second stage are felt to be reasonable in this case in which the second stage is carried internal to the first stage.

The proposed pop-up maneuver plus the addition of a second stage to improve the payload capability of a SSTO vehicle is a TSTO reusable launch vehicle option. While an SSTO-performance-capability first stage was assumed in the Air Force Research Laboratory study, it is not at all clear that an SSTO-capable first stage MSP is the preferred first stage for this class of TSTO option.

An SSTO-capable first-stage, whether rocket, air-breathing, or combined cycle engine powered, places extreme demands on current technology. The NASP Joint Program Office did not produce an SSTO-capable final design. Additional technology advances were required to achieve the required propellant mass fraction. The Air Force Have Region structural test program in the 1980s left the question of achievable mass fraction unresolved for a rocket-powered SSTO. NASA is currently investing almost $1 billion in the Lockheed-Martin Skunk Works X-33 program to demonstrate the technical feasibility of a rocket-powered SSTO.

The 1994 and the 2000 Air Force Scientific Advisory Board (AF SAB) studies looked at the issue of a SSTO reusable launch vehicle. While the AF SAB felt that in the long term an SSTO might achieve significant reductions in payload-to-orbit cost, they did not believe the technology was available at this time to build an SSTO. The consensus was that a TSTO reusable was achievable and should be the next generation launch vehicle.

Most SSTO designs today are configured to deliver payload into low Earth orbit. Military and commercial satellites in general require additional stages to deliver satellites to their operational orbits. As a consequence two or more stages are needed to place the payload into the operating orbit. The issue confronting space launch designers today is not whether a SSTO, or TSTO launch vehicle is the preferred choice, but rather what the number of stages and staging Mach number(s) should be for a launch vehicle to deliver the payload directly into the operating orbit, or a transfer orbit with an apogee at the operational orbit. In the latter case the spacecraft propulsion system provides the final insertion velocity.

Reusable launch vehicle performance requirements are usually based on payload delivery to low Earth orbit, or the international space Station orbit. However, military and commercial satellites in general require upper stages to deliver satellites to operational orbits from either a parking orbit or a direct transfer orbit. As a consequence two or more stages are needed to place the payload into the operating orbit. Therefore, the launch vehicle should be configured to deliver the payload into the operational orbit, or into a transfer orbit to the operational orbit, and let the satellite provide the final insertion into the operating orbit. Increasing the velocity requirements to be provided by a reusable launch vehicle could significantly increase the staging Mach number for a TSTO reusable launch vehicle as illustrated by the GEO payload case provided in this paper.

Previous TSTO design concepts have considered subsonic (Mach 0.4-0.8), supersonic (Mach 2-4), and hypersonic staging (Mach 5-10). However, these studies usually considered TSTO designs for low Earth orbit missions. Reference 5 presents a case for increasing the staging Mach number to Mach 23+ in order for the first stage to have a global-range performance capability.

Two TSTO studies were used to show the impact of staging Mach number on launch vehicle performance. Reference 8 is a study done in 1990 by the German Aerospace Research Establishment -DRL. The German study included eight SSTO concepts and eight TSTO concepts. TSTO concepts considered Mach 3 and 6 staging. Both propellant and propulsion options were considered. Reference 9 is a study done in 1978 for the NASA Langley Research Center. The Langley included two SSTO design concepts and five TSTO design concepts. Staging Mach numbers were 0 (SSTO), 3.2, and 10. The mission in each study was a 100 n. mi. low Earth orbit.

The results of these two studies are summarized on figure 13. The TSTO performance optimum staging occurs in the Mach 3-12 range, depending on propulsion system selection. Whereas, the pop-up optimum Mach number case in Reference 3 is between Mach 8-12. The Mach 23 staging case is approximately 10-20% less than the optimum. As the mission velocity requirements increase, the optimum staging Mach number increases as indicated on figure 11 for a GEO payload mission.

CONCLUSION

There is current interest in TSTO reusable launch vehicles based on experience in both the National AeroSpace Plane program and the current X-33 program. It is generally perceived that a TSTO reusable launch vehicle would be more robust, more reliable, and less risk than a SSTO reusable launch vehicle. Previous TSTO launch vehicle studies have indicated that the performance optimum staging Mach number for a TSTO reusable launch vehicle is between Mach 5-10 depending on which propellants and propulsion systems are used. The Air Force Research Laboratory has proposed a rocket powered TSTO reusable launch vehicle based on a SSTO capable first stage, and a pop-up trajectory profile to facilitate the recovery of the first stage. This paper presents a hydrogen-oxygen rocket-based combined cycle engine powered Mach 23 staged TSTO reusable launch vehicle option. A Mach 23 performance capable first stage would be less risky than a SSTO capable first stage. The usable propellant fraction requirement for a Mach 23 first stage performance capability is O.614 compared to a SSTO performance capable first stage of 0.790. A Mach 23 first stage is also capable of unrefueled global range using a boost-glide-skip trajectory profile, which would facilitate the recovery of the first stage without the need for additional recovery bases, as is the case with the pop-up trajectory option.

Dual use of the first stage has been a recent topic of discussion for TSTO reusable launch vehicles. It has been proposed that the first stage of a TSTO reusable launch vehicle be used as a hypersonic cruiser. However, there are significant differences in the design features between a cruiser and the first stage of a TSTO vehicle. The first stage of a TSTO vehicle is an accelerator requiring a high thrust to weight at take-off. Optimum thrust to weight ratios for the first stage vary form 0.5 to 1.3 depending on the design and the type of propulsion system used. The optimum thrust-to-weight ratio at take-off for a cruiser varies from 0.25-0.35. A cruiser could also require more thermal protection than a first stage depending on the staging mach number of the TSTO design. While technology used for a TSTO launch vehicle might be shared, two separate vehicle designs could be needed to meet the performance requirements for the first stage and a cruiser.

A Mach 5-10 cruiser optimized design for maximum range would not have a global range mission capability without the use of in-flight refueling. In-flight refueling is a difficult operation at best for a subsonic aircraft, and an even more difficult operation for a Mach 5-10 aircraft. Hypersonic aircraft do not fly well subsonically, which would be required for in-flight refueling. In the case of the proposed Mach 23 staged TSTO reusable vehicle, an unrefueled global range flight occurs during each mission. Only one vehicle would have to be developed for both orbital and global range missions.

ACKNOWLEDGMENTS

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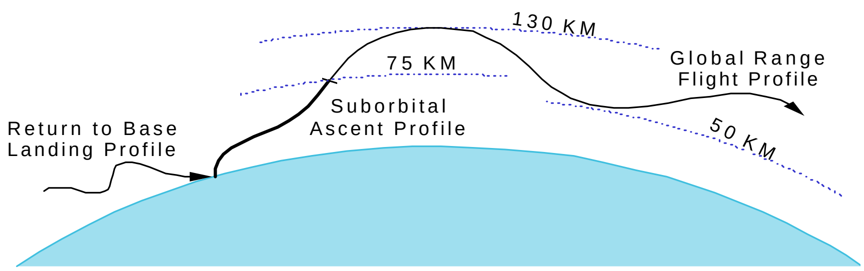

Figure 1. The Flight Profile Characteristics of a Boost-glide-Skip Trajectory

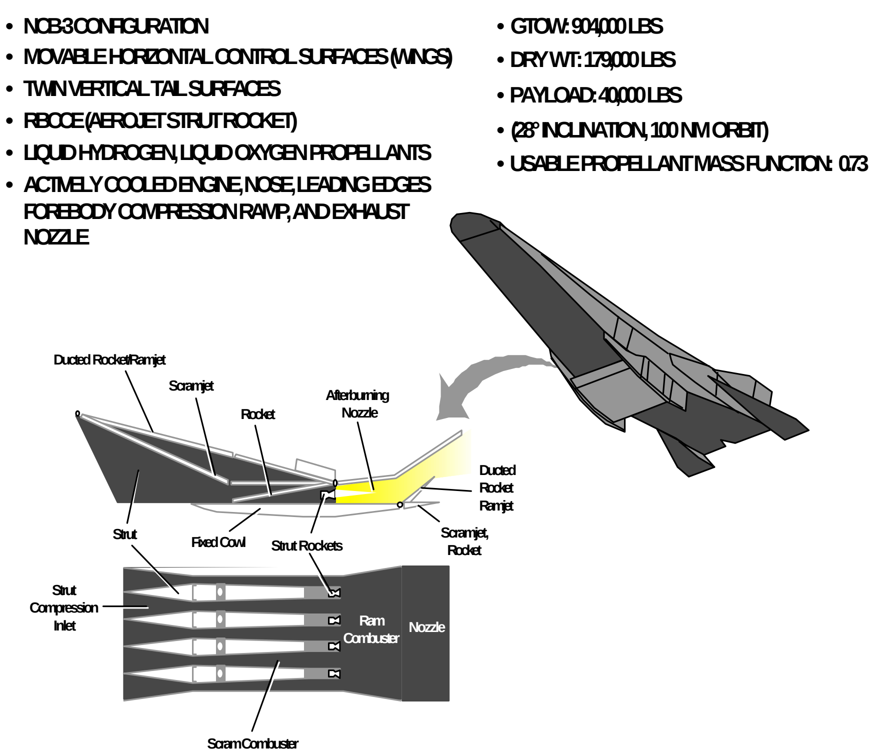

Figure 2. Reference SSTO Design Concept and Propulsion System

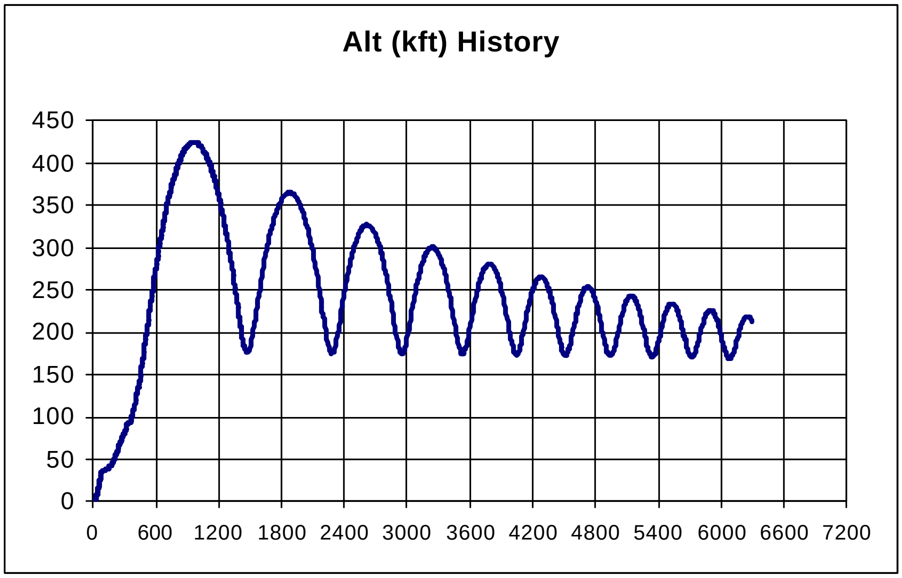

Figure 3.

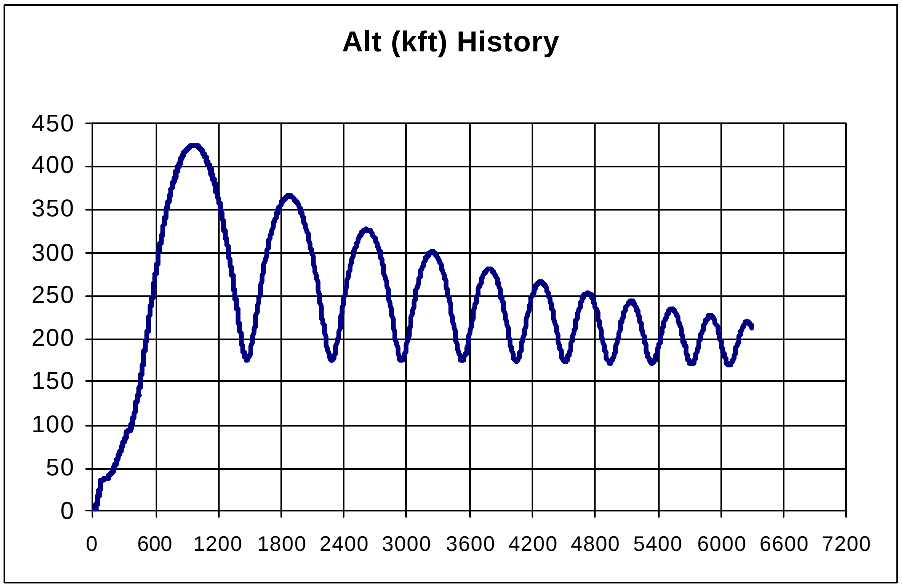

Figure 4.

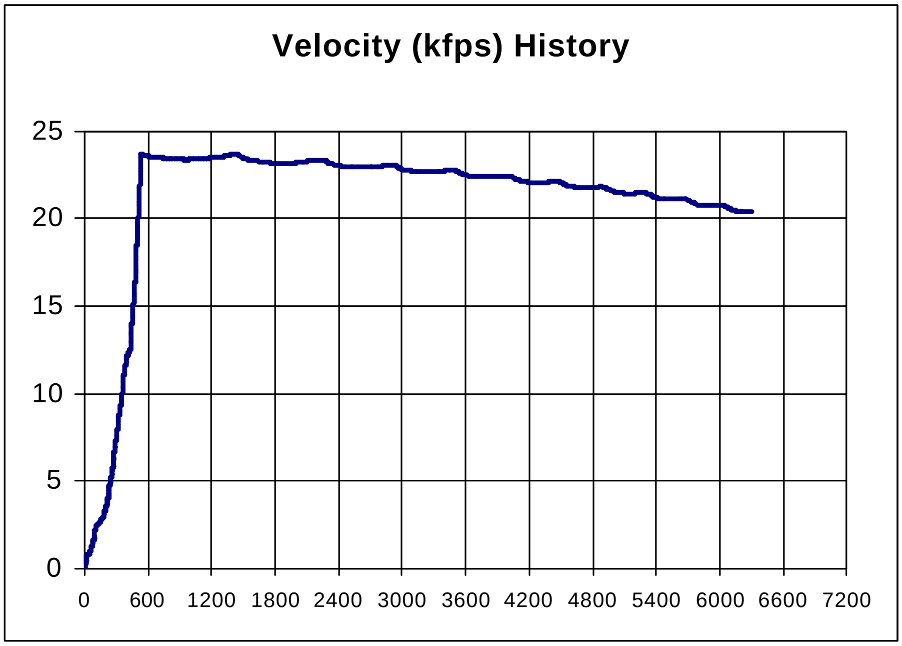

Figure 5.

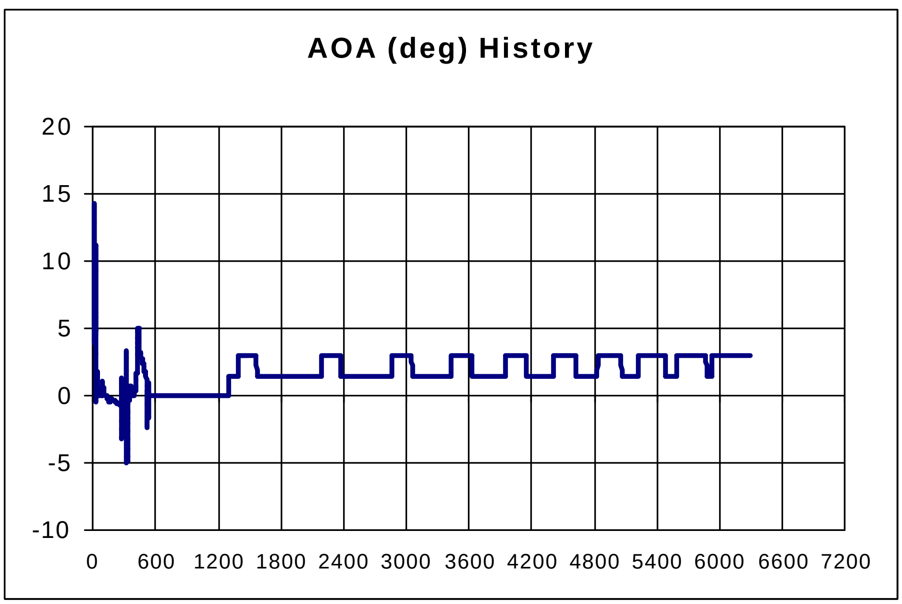

Figure 6.

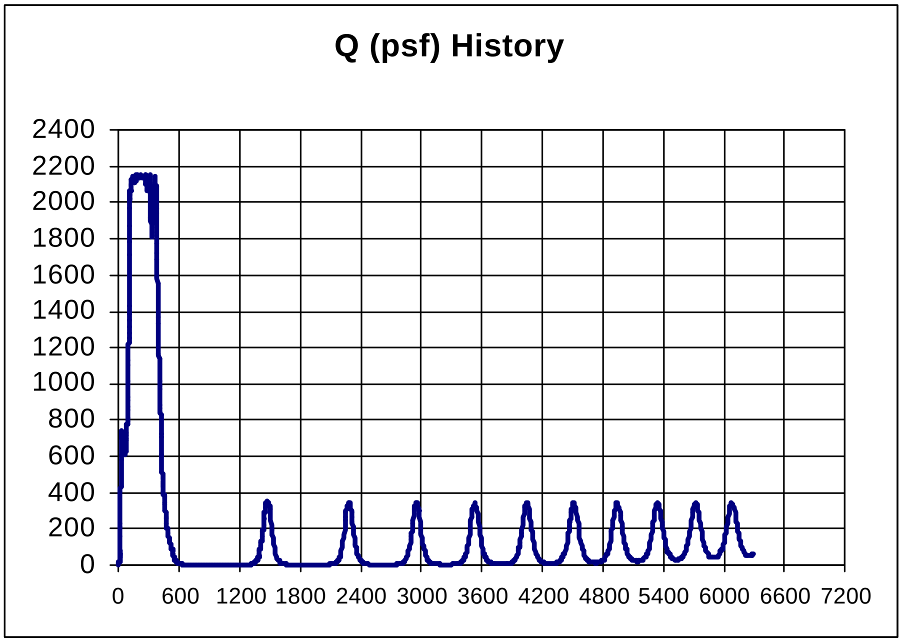

Figure 7.

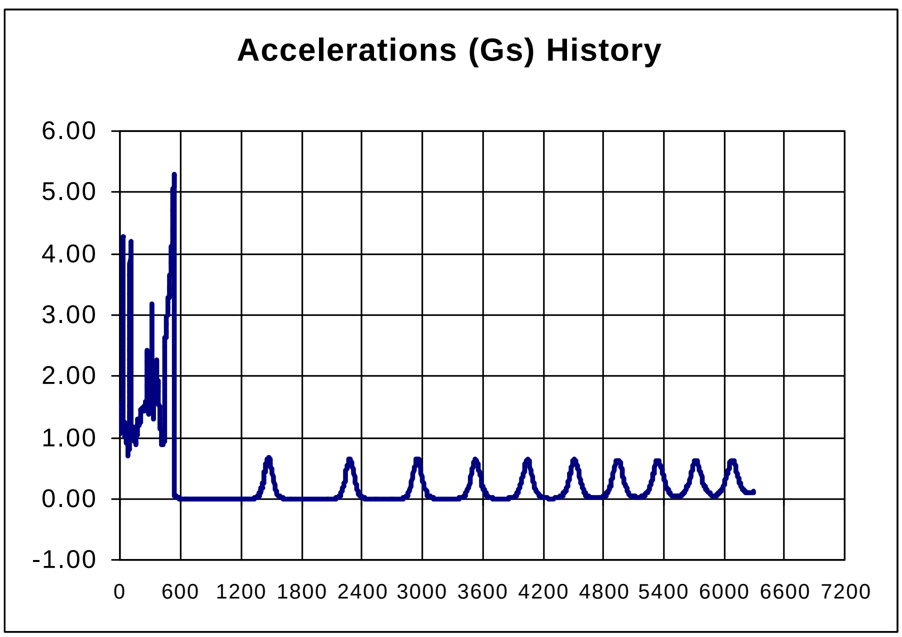

Figure 8.

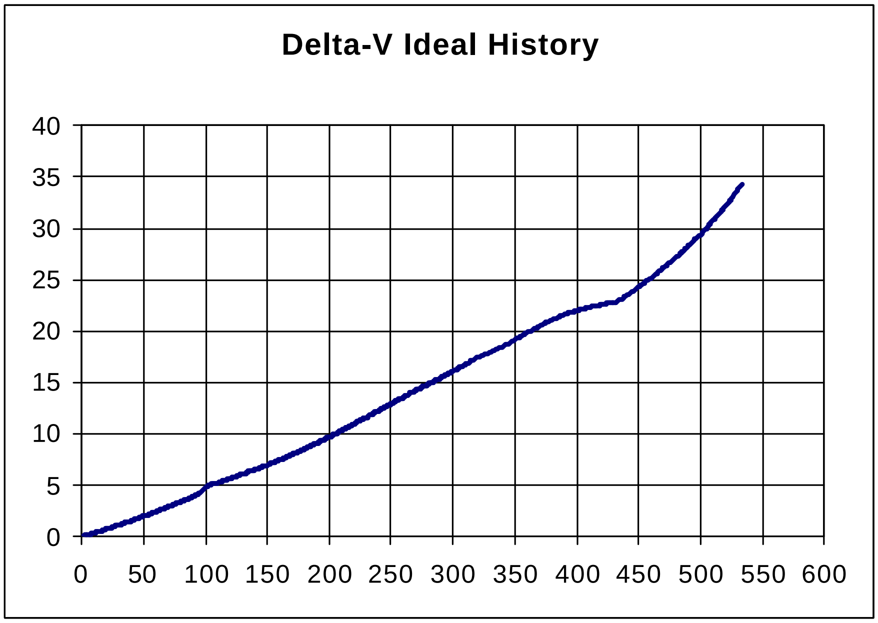

Figure 9

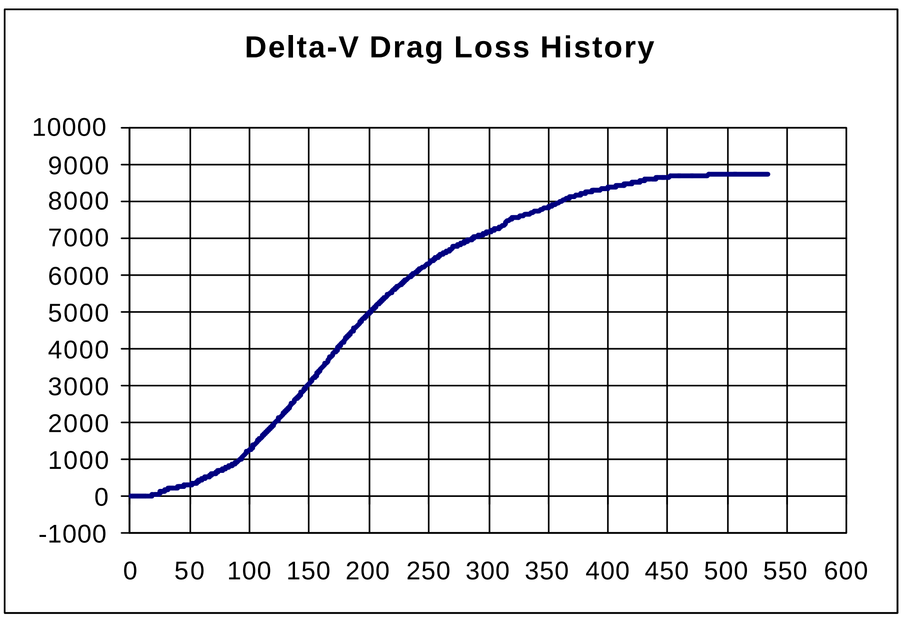

Figure 10

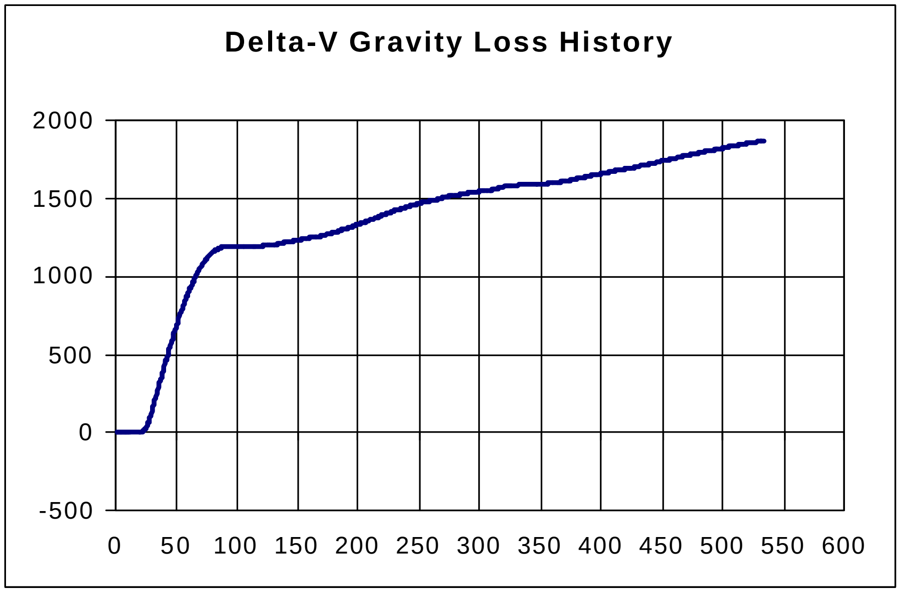

Figure 11

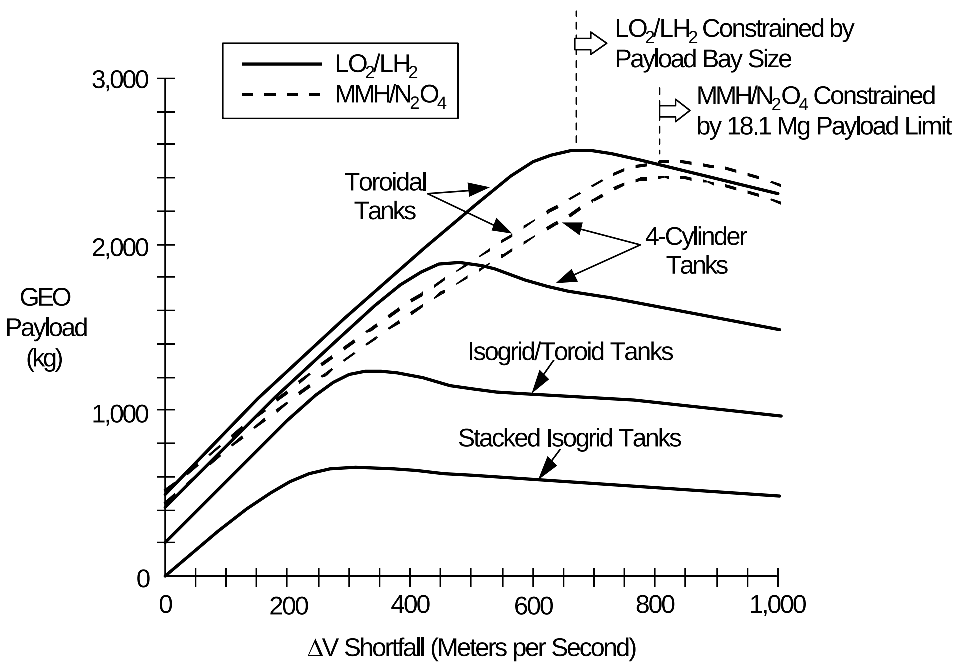

Figure 12- Effects of Tank Configuration and Propellant Selection on GEO Payload Performance

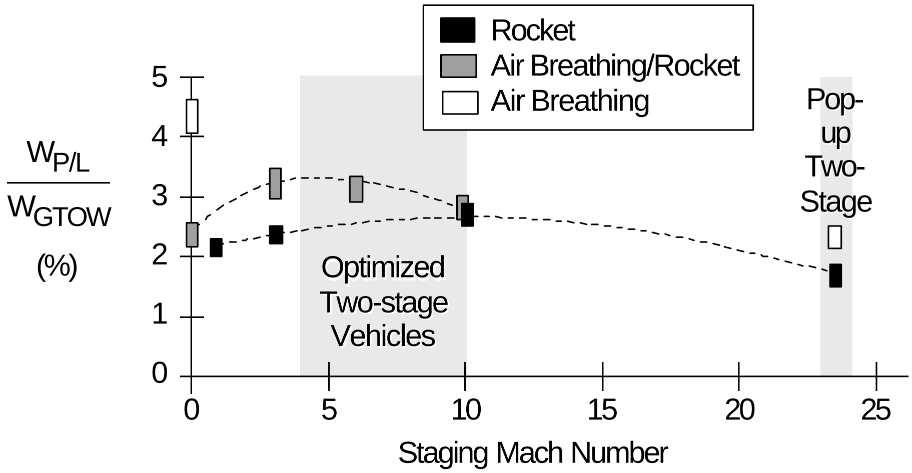

Figure 13. Typical Performance Summary for SSTO and TSTO Launch Vehicles

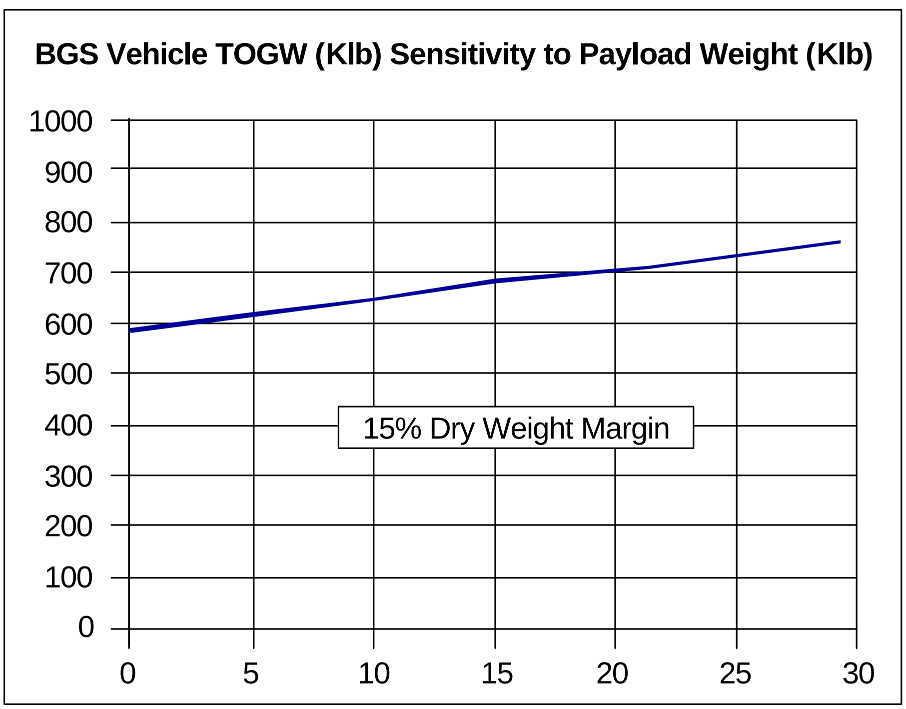

Figure 14

Table 1. Reference Vehicle Weight Data

ITEM	SUB-ITEM WEIGHT (w/ MARGIN)
AIRFRAME STRUCTURE	123581.010
WING	0.000
WING TPS	0.000
FUSELAGE	85515.225
FUSELAGE TPS	14081.339
TAIL	9936.453
SURFACE CONTROLS	1164.552
LANDING GEAR	12883.450
PROPULSION	96357.350
SCRAMJET ENGINES, 4.0	43023.800
ROCKET WITH STRUCTURE	4080.200
LOW SPEED ENGINES	33270.650
INLET AND NACELLES	3847.000
FUEL SYSTEM	12133.650
FIXED EQUIPMENT	19525.850
FLIGHT CONTROLS	8703.200
ELECTRICAL	3018.750
ELECTRONICS/AVIONICS	1591.600
CREW FURNISHINGS	948.750
ENVIRON. CONTR. SYS.	3945.650
AUXILIARY POWER SYSTEM	1317.900
EMPTY WEIGHT	239464.2
USEFUL LOAD	4183.000
CREW AND BAGGAGE	472.000
RESIDUAL LIQUIDS	3711.000
FUEL	128876.399
TAKEOFF	4176.384
CLIMB	102675.612
ROCKET (LH2)	20299.503
TAKEOFF	0.000
CLIMB	20299.503
BOIL OFF (LH2)	1723.901
OXIDIZER (LOX)	304786.668
TAKEOFF	24618.703
CLIMB	280167.960
CONSUMABLES (LIQ&GAS)	6262.000
PAYLOAD	23000.000
PASSENGERS	170.000
BAGGAGE	40.000
CARGO	22790.000
TOGW	706572.3
PROPELLANT FRACTION	**61.3756%**
LOX FRACTION OF PROPELLANT	**70.2820%**